I. Abstract

With economic incentive, even small farmers can augment biodiversity across a landscape. Therefore, the economy of local people living on degraded land is an important factor in conservation. As restoration ecologists with conservation goals, we are mostly interested in restoring native species. However, early results of our 20 years of experiments on severely eroded pasture in southern Costa Rica forced us to consider alternatives. Planting a non-native species has proved a solution. Our approach applies to deeply eroded land on which both ecological and economic benefits are goals of restoration.

Our methods included:
- testing what kinds of trees could grow across our site;
- testing if successful species could “nurse” (facilitate growth of) other trees;
- studying the most successful species in depth to determine their ecological and economic benefits.

Here we report on our most successful species, *Pinus tecunumanii* (originally part of “oocarpa”), native from Mexico to Nicaragua. This species is thought to have low invasive potential. In our study it rebuilt topsoils in the worst places at our site where no other species could grow. Furthermore, it produced valuable wood harvestable in 15 years.

We studied four of its potential disadvantages as a non-native.

1. Might this species of pine become invasive?
2. Might this non-native reduce biodiversity, especially if planted in dense plantations?
3. As an ectomycorrhizal (ECM) species, might pine inhibit the arbuscular mycorrhizal fungi (AMF) needed by native trees, eventually rendering the soil hostile to natives?
4. Might this pine prevent recruitment of native species?

(1) The few cones produced usually contain no seed. Seeds so far are infertile. (2) Our model of planting small stands of pines in places with the worst conditions did not reduce biodiversity of invertebrates or birds compared to native stands. (3) Even dense stands of pine did not inhibit colonization by the arbuscular mycorrhizal fungi needed by native trees. Also, the pine itself was colonized by AMF and therefore may act as a source of those fungal spores. (4) Planted seedlings of native species were able to grow under this pine.

We conclude that *Pinus tecunumanii*, specifically, may be of value for beginning restoration of ecosystem services to extremely degraded land and for providing an economic benefit to landowners. Farmers may plant it in the worst parts of their farms in a patch rotation model.
II. Introduction

We chose 20 years ago to study forest and soil restoration on a deeply eroded cattle pasture in Coto Brus, southern Costa Rica.
  • Originally interested in enhancing biodiversity, we expanded our research to address economic as well as ecological benefits in order to be a useful model for the people of the region.
  • As a first step, tree trials determined what species could survive the stressful conditions of degraded pasture.
    – Of the successful species, we asked if they could facilitate (“nurse”) growth of less successful species when mixed with them.
  • We studied the four most successful genera in depth.

Here we present results of tree trials and our studies on the species that had by far the highest survival and growth, *Pinus tecunumanii* (“oocarpa”). This non-native pine was the only Angiosperm able to grow in our worst sites. Our question is whether this non-native species might be used judiciously, as has pine in Puerto Rico, to restore some ecological as well as economic value to deeply eroded areas on long mismanaged farms such as ours was.

III. Methods

  • Site 10km so. of Las Cruces, southwest Costa Rica
    – 1050m elevation; 4500 mm annual precipitation
    – Rugged terrain with small valleys, steep slopes, high ridges.
    – Soils: Ultisols with Andic influence, phosphorous-fixing, acid, infertile:
      
      | Initial soil chemistry in 1993 (0-15cm), means based on N=45 |
      |-----------------|-----------------|-----------------|-----------------|
      | pH  | AL (% sat) | PO4 (μg/g) | OM (%) |
      | 5.0 | 34          | 0.6         | 5.4    |
      |     |             |             | Total N (%) | NH4 (μg/g) | NO3 (μg/g) |
      |     |             |             | 0.3     | 7.2       | 54.7       |

    – Erosion to B or C horizon, to bedrock in places; initial plant cover averaged <50%

  • **PART 1. Tree trials: What species tolerate severely eroded conditions?**
    – Formal trials in 1994, ‘96, ‘98 with 7-9 species each, 3 individuals per species/plot, total 89 plots.
    – 2 non-natives in 1994, including *Pinus tecunumanii* (previously included in *oocarpa*, genetically close to *oocarpa*)
– Informal trials whenever we could get seeds (9 more native species).
– Total 32 species (29 natives)

• **PART 2. *Pinus tecunumanii***:
  What benefits does this pine species yield at our site?
  – 29 21x12m plots planted with 3 pines 3m apart in rows, mixed with rows of 3 individuals each of 5 natives and one non-native, forming small mixed-species stands
  – At 13-14 yr, soils sampled under pine, *Vochysia*, and natural regeneration
  – At 17yr, one pine thinned from each of 10 plots and the lumber extracted and valued.

What are the ecological disadvantages of this pine species?
1) Could this pine become invasive?
   – Cones assessed several years for fertile seeds
2) Biodiversity assessment: Does this pine reduce diversity?
   • Arthropods pit-trapped under pine, native trees, pasture, secondary forest.
   • Birds counted in 24x12m plots of pine plantation, mixed pine stand, charral (natural regeneration with native species), pasture and secondary forest
3) Mycorrhizal colonization: Does this pine inhibit arbuscular mycorrhizal fungi (AMF)?
   Pines are ectomycorrhizal (ECM) whereas most natives need AMF
   • Pine and Angiosperm roots sampled in a neighboring dense pine plantation and in our small 1994 mixed stands of pine
   • Determined % root tips colonized by ECM fungi
   • Determined % grid intersections touching AMF hyphae in microscopic sections of both pine and Angiosperm roots
4) and 5) Does pine inhibit native seedlings?: Two studies:
4) 2004 facilitation experiment:
   • Pine seedlings as shade control in testing if *Vochysia* seedlings can nurse seedlings of *Astronium graveolens*
   • 4 blocks with 2 nurse tree treatments (n=40) and the pine control (n=20)
5) 2006 facilitation experiment:
   • Mature pine as shade control in testing if mature *Vochysia* can nurse seedlings of four other native trees, *P. pinnatum, C. brasiliense, T. chrisantha,* and *A. graveolens*
   • 6 blocks with 1 nurse tree treatment (n=18 per species) and 1 pine control (n=42 per species).

IV. Results and Discussion

PART 1. Tree trials showed few species survived well.

• Three formal trials
  – Most species had 60-96% mortality (TABLE 1)
  – 5 natives and 2 non-natives had stable survival and growth (shaded in Table 1)
  – All but pine had much lower growth than values in the literature (FIG. 1)
• Informal trials
  – Only single individuals of 9 other species survived.

### Table 1
Mortality and Growth in Tree Trials

<table>
<thead>
<tr>
<th>species</th>
<th>% mortality</th>
<th>cm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vochysia guatemalensis</td>
<td>20</td>
<td>89</td>
</tr>
<tr>
<td><em>Pinus oocarpa</em></td>
<td>21</td>
<td>138</td>
</tr>
<tr>
<td>Calophyllum brasiliense</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Terminalia amazonia</td>
<td>61</td>
<td>47</td>
</tr>
<tr>
<td>Cedrela odorata</td>
<td>69</td>
<td>50</td>
</tr>
<tr>
<td>Eucalyptus deglupta</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>Tabebula chrysanthia</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td><em>Inga spectabilis</em></td>
<td>6</td>
<td>41</td>
</tr>
<tr>
<td><em>Vochysia ferruginea</em></td>
<td>13</td>
<td>57</td>
</tr>
<tr>
<td><em>Inga edulis</em></td>
<td>34</td>
<td>45</td>
</tr>
<tr>
<td>Astronium graveolens</td>
<td>43</td>
<td>12</td>
</tr>
<tr>
<td><em>Terminalia amazonia</em></td>
<td>43</td>
<td>24</td>
</tr>
<tr>
<td>Aspidosperma spruceanum</td>
<td>73</td>
<td>17</td>
</tr>
<tr>
<td><em>Annona</em></td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Cedrella tonduzii</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Platymiscium pinnatum</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schizolobium parahyba</td>
<td>13</td>
<td>35</td>
</tr>
<tr>
<td><em>Inga edulis</em></td>
<td>24</td>
<td>69</td>
</tr>
<tr>
<td>Myracroma oblonga</td>
<td>28</td>
<td>90</td>
</tr>
<tr>
<td><em>Diphysea robinoides</em></td>
<td>37</td>
<td>31</td>
</tr>
<tr>
<td>Callandra calothyrsus</td>
<td>38</td>
<td>98</td>
</tr>
<tr>
<td><em>Terminalia amazonia</em></td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td>Albizia carbonaria</td>
<td>57</td>
<td>40</td>
</tr>
<tr>
<td>Platymiscium pinnatum</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td><em>Glicidia sepium</em></td>
<td>86</td>
<td>29</td>
</tr>
</tbody>
</table>

**Fig. 1**
Comparing our growth rates with conservative values in the literature.

![Graph showing growth rates comparison](image)

**PART 2. *Pinus tecunumanii* : Benefits and Potential Ecological Disadvantages**

**Benefits**

• **Pine dominated the 1994 tree trial**
  – Only pine survived and grew in barren patches (see example below left) and on high ridges (see example below right)

---

**An eroded plot at 6 yr:**
Six other species were planted in this plot. All 3 pines still survive; all other trees died.

**Four ridge plots:**
Along the high ridge we planted 12 individuals of each of 7 species in 1994 (n=84). Ten of 12 pines thrived, while 69 of the other 72 trees died.
Soils are least fertile and most eroded on ridges and slopes (TABLE 2) but this pine tolerates these conditions well.

### TABLE 2
Soils in Three Terrains

<table>
<thead>
<tr>
<th>Valleys versus slopes</th>
<th>pH *</th>
<th>AL (% sat) **</th>
<th>PO4 (ug/g) ***</th>
<th>OM (%) **</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>4.8</td>
<td>10</td>
<td>0.7</td>
<td>7.4</td>
</tr>
<tr>
<td>S</td>
<td>4.5</td>
<td>32</td>
<td>0.3</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NH4 (ug/g) ***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>4.4</td>
<td>17.9</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>2.6</td>
<td>3.0</td>
<td>8.9</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Slopes versus ridges</th>
<th>pH **</th>
<th>NO3 (ug/g) **</th>
<th>CICE (cmol(+)/L) **</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>5.0</td>
<td>2.8</td>
<td>10.7</td>
</tr>
<tr>
<td>R</td>
<td>4.7</td>
<td>4.0</td>
<td>8.6</td>
</tr>
</tbody>
</table>

- At 14 yr, soils under pine had twice as much available P as under *Vochysia* and in natural regeneration
  - Soils under pine had significantly (p<.01) lower pH than in 1994
  - The increment decrease was small and not thought to be important for the acid-adapted natives.
- Pines were harvestable by 15 yr
  - 10 thinned trees (right) yielded 2300 board ft=$2400 today

Are there ecological disadvantages to using this pine species?

1) At 19 yr, no fertile seeds yet, in contrast to *P. caribea* in a neighboring plantation, which is invading our site.
2) Biodiversity measures were not reduced in mixed stands of pine
  - H' of pit-trapped arthropods was second-highest in pine stand
    - H' increased with canopy cover (p < .01)
    - Pine stand and secondary forest had the highest canopy cover
    - Therefore, pine did not inhibit arthropod diversity
  - Bird S was second-highest in pine stand (FIG. 2)
    - Pasture < pine plantation < char rall (natural regeneration) < mixed pine stands < secondary forest
3) Pine ectomycorrhiza did not inhibit AMF colonization
   - ECM colonization of pine was higher in plantations than in small stands (p=.03)
   - Surprisingly, pine roots also contained AMF (FIG. 3A)
     - Degree of AMF colonization was just as high in plantations as in small mixed stands (p=.28) despite more ECM
   - Importantly, Angiosperms growing under pines were normally colonized by AMF (FIG. 3B)
     - Even in dense plantations (no difference, p=.29)
   - Therefore, no inhibition occurred and pines might even benefit natives by acting as sources of AMF spores

4) In the 2004 facilitation experiment pine helped native Astronium
   - (photo: indicating top of Astronium at 9 yr)
   - Astronium survival (p<.03) and growth (p<.02) were greater under pine than under the native Vochysia
   - Astronium grew almost twice as fast with pine as in the pasture tree trial (see Table 1, 1996 Trial)

5) The 2006 facilitation experiment showed mixed results for mature pine:
   - After 4 years, survival for two of four species was lower under pine than under Vochysia (FIG. 4 top)
Their survival was still high compared to pasture tree trials.
- Height growth did not differ under pine and *Vochysia* (FIG. 4 bottom, p>.08 for all species)
  - Nor did volume growth differ
- Under pine, 3 of 4 species survived and one grew better than in pasture (Tree Trials 1994, ‘96).

V. Conclusions

- Only a few tree species can establish cover, reduce erosion, and help rebuild topsoils at extremely eroded sites.
  - *Pinus tecunumanii* and three of our natives are yielding ecosystem benefits
- **Only the pine grows well enough to be harvestable, yielding the economic benefit of potential income.**
- We so far have found no ecological disadvantages of using this pine to begin restoration, even though it is not native.
  - Unlike other pines it does not reproduce at our site, so has low invasiveness,
  - Even when mature, it allows some natives to grow in its shade,
  - It does not inhibit mycorrhizal colonization of other species,
  - It increases plant community structure, increasing diversity of small organisms.
- We only recommend *P. tecunumanii* because of many of its traits, including low invasive potential.
  - This is by far the best species economically for Neotropical middle elevations.
- We envision a patch rotation model as the best way to use pine
  - Every farm consists of productive and unproductive patches (FIG. 5).
  - Plant pine in the unproductive patches
    - Seedlings of late-successional valuable hardwoods could be mixed with pine

FIG. 5: Mosaic of landscape usage

Higher ridges and sub-ridges (red brackets) are infertile > use pine
Eroded bare areas (dashes) are infertile > use pine
Keep valleys (blue) and lower slopes in productivity
– In 15-20 years harvest the pine and return the patch to crop productivity
  o or, allow planted hardwoods to continue to grow after pines are removed
  – Plant pines in other patches which have become unproductive in the meantime.
• This model would create a dynamic system and patchy landscape that should enhance biodiversity compared to many other kinds of land-use, as well as yield economic benefits to the landowner.